Title: SEM Resolution Improvement Using Semi-Blind Restoration with Hybrid L1-L2 Regularization

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SEM Resolution Improvement Using Semi-Blind Restoration with Hybrid L_1-L_2 Regularization

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Outline

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1. Introduction
2. Scanning Electron Microscope Imaging
   - Physics on Scanning Electron Microscope
   - Restoration and Regularization Theory
3. Semi-Blind SEM Image Restoration
4. Experimental Results
   - Experiment 1: Gold on Carbon Pela Standard 617-4
   - Experiment 2: Tin Ball Standard Pela 620-a
5. Conclusions

Introduction

- Scanning electron microscopy (SEM) resolution is limited by many factors that include sample specific properties, microscope stability, noise, the three dimensional nature of the sample and the excitation volume, and the spatial distribution of electrons in the probe known as the point spread function (PSF).
- The loss of SEM imaging resolution is principally due to blurring by the convolution of the PSF with the specimen structure of interest.
- The resulting image resolution can then be increased by post-processing (restoration) combined with the mathematical process known as regularization.
- We develop a novel high resolution semi-blind image restoration technique incorporating hybrid L_1 and L_2 regularization terms.

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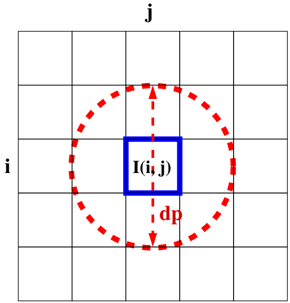


An illustration of electron beam interacting with specimen.

- The center of the electron beam is focused on the specimen pixel $I(i, j)$, while the diameter of the probe is d_p.
- The size of probe, d_p plotted in red is larger than the specimen pixel size plotted in blue.

Physics on Scanning Electron Microscope

The detected signals is actually a weighted summed values of all the pixels covered by the probe (the PSF). Denoting the actual observed signal intensity on a display as, $I'(x, y)$, we can pose the relationship between the actual amount of signal, $I(x, y)$ and the observed, $I'(x, y)$ as,

SEM Imaging

$$I'(x, y) = psf(x, y) \otimes I(x, y) + k(x, y),$$

where *psf* is the point spread function, k is the additive noise during the imaging process and the operator $\otimes$ means the spatial convolution.

Physics on Scanning Electron Microscope

The corresponding matrix-vector formulation is posed as,

SEM Imaging (Matrix Form)

$$\mathbf{I_c} = A\,\mathbf{I_t} + \mathbf{k},$$

where $\mathbf{I_c}$, $\mathbf{I_t}$, and $\mathbf{k}$ represent the lexicographically ordered vectors of the quantities $I'(x, y)$, $I(x, y)$, and $k(x, y)$, respectively, and A is the 2-D matrix representation of the PSF spatial function $psf(x, y)$.

Physics on Scanning Electron Microscope

The inverse problem of the aforementioned SEM imaging is to remove the PSF function from a given image, which can be posed as a least-squares fit mathematically,

Restoration on SEM Imaging

$$E(\mathbf{I_t}) = \min_{\mathbf{I_t}} \left\{ \|\mathbf{I_c} - A\,\mathbf{I_t}\|_2^2 \right\}.$$

Regularization Theory

In order to alleviate the ill-posedness, the regularization technique is applied to the image restoration. The general formulation of least-squares restoration with a regularization term can be posed as,

SEM Image Restoration with Regularization

$$E(\mathbf{I_t}) = \min_{\mathbf{I_t}} \left\{ \|\mathbf{I_c} - A\,\mathbf{I_t}\|_2^2 + \lambda \mathrm{R}(\mathbf{I_t}) \right\},$$

where the term of $\mathrm{R}(\mathbf{I_t})$ is the regularization term and the parameter λ is the regularization parameter.

Regularization Theory

Tikhonov regularization and total-variation (TV) regularization are the most commonly used [*Vogel-2002*, *Osher-1992*].

- The Tikhonov regularization is defined as,

Tikhonov regularization

$$\mathrm{R}(\mathbf{I_t}) = \|\mathbf{I_t}\|_{\mathrm{TK}} = \|H\mathbf{I_t}\|_2^2,$$

where the matrix H is usually defined as a high-pass filtering operator, or an identity matrix.

- The TV regularization is defined as,

TV regularization

$$\mathrm{R}(\mathbf{I_t}) = \|\mathbf{I_t}\|_{\mathrm{TV}} = \sum_{1\le i,j\le n} \sqrt{|(\nabla_x \mathbf{I_t})_{i,j}|^2 + |(\nabla_y \mathbf{I_t})_{i,j}|^2}.$$

Outline

Semi-Blind SEM Image Restoration

- The semi-blind SEM imaging technique with hybrid L_1-L_2 regularization is given below:

Semi-Blind SEM Image Restoration

$$E(A, \mathbf{I_t}, \mathbf{u_t}) = \min_{A, \mathbf{I_t}, \mathbf{u_t}} \quad \{\|\mathbf{I_c} - A\mathbf{I_t}\|_2^2 + \lambda\|HA\|_F^2 + \mu\|\mathbf{I_t} - \mathbf{u_t}\|_2^2 + \eta\|\mathbf{u_t}\|_{\mathrm{TV}}\},$$

where $\mathbf{u_t}$ is an auxiliary variable, and λ, μ and η are all regularization parameters.

- The term, “Semi-Blind”, is due to the fact that the blurring kernel is unknown and also needs to be estimated from the restoration.

Semi-Blind SEM Image Restoration

An alternating-direction minimization method to solve for the three independent variables is employed, which leads to three sub-problems :

Sub-problems

$$A^{(k)} = \underset{A}{\operatorname{argmin}} \left\{ \left\| \mathbf{I_c} - A\mathbf{I_t}^{(k)} \right\|_2^2 + \lambda \left\| HA \right\|_F^2 \right\},$$

$$\mathbf{I_t}^{(k)} = \underset{\mathbf{I_t}}{\operatorname{argmin}} \left\{ \left\| \mathbf{I_c} - A^{(k)}\mathbf{I_t} \right\|_2^2 + \mu \left\| \mathbf{I_t} - \mathbf{u_t}^{(k)} \right\|_2^2 \right\},$$

$$\mathbf{u_t}^{(k)} = \underset{\mathbf{u_t}}{\operatorname{argmin}} \left\{ \mu \left\| \mathbf{I_t}^{(k)} - \mathbf{u_t} \right\|_2^2 + \eta \|\mathbf{u_t}\|_{\mathrm{TV}} \right\}.$$

Semi-Blind SEM Image Restoration

- The three subproblems have distinct physical meanings.
  - The first sub-problem solves for the variable A, which is the process of the PSF function estimation [*Lishin-2014*].
  - The second sub-problems solves for the variable $\mathbf{I_t}$ using a conventional SEM imaging with a Tikhonov regularization, therefore artifacts due to the ill-posedness of the inverse problem may be suppressed.
  - The third sub-problem is a typical TV-denoising problem, therefore the auxiliary variable $\mathbf{u_t}$ becomes a TV-denoised result of $\mathbf{I_t}$ with the object edges sharpen.
- By solving all three subproblems respectively, a sequence of iterations are generated, that converges on the restoration result,

$$A^{(0)} \rightarrow \mathbf{I_t}^{(1)} \rightarrow \mathbf{u_t}^{(1)} \rightarrow \cdots \rightarrow A^{(k)} \rightarrow \mathbf{I_t}^{(k+1)} \rightarrow \mathbf{u_t}^{(k+1)}.$$

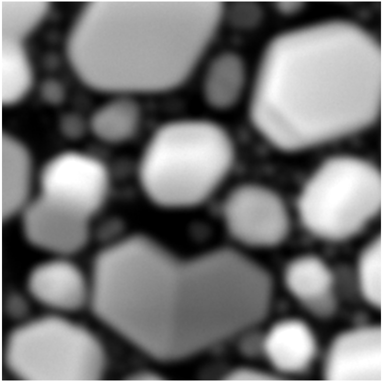
- The interleaving of solving these three sub-problems leads to a restoration that not only improves the minimization of the data misfit, but also enhances the sharpness of object edges.

Outline

Experiment Setup

- The “reference microscope” is a defined as the instrument that is capable of high resolution that can obtain images with probe size smaller than the pixel size .
- The “observation microscope” are collected at 20 keV using a TESCAN VEGA LaB6 source SEM.
- The “observation microscope” has probe size bigger than the pixel size.
- Two samples are tested using our restoration algorithm:
  - The first reference sample used is a pela 617-4 gold particle on carbon standard.
  - The second reference sample is a tin ball standard Pela 620-a.

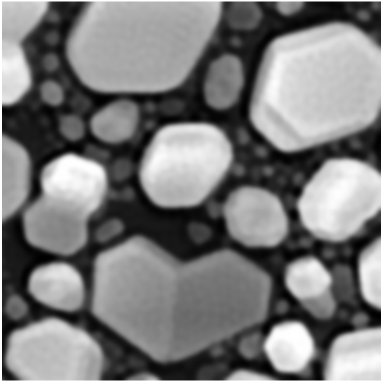
Experiment 1: Gold on carbon Pela Standard 617-4



Observation Microscope

- The observed image is blurry.

Experiment 1: Gold on Carbon Pela Standard 617-4



Restored Image

- Both the big and small particles are better resolved.
- The edges of the particles are sharpened.

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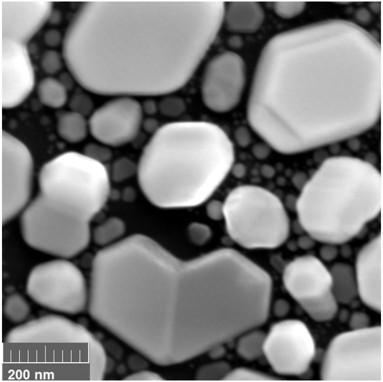
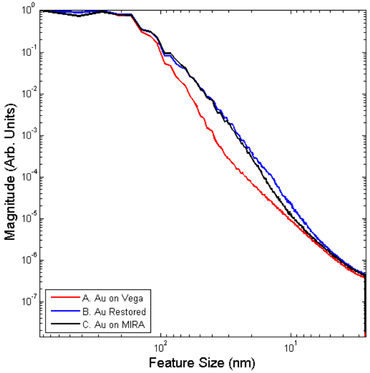


Reference Image

- Gold on carbon Pela Standard 617-4.

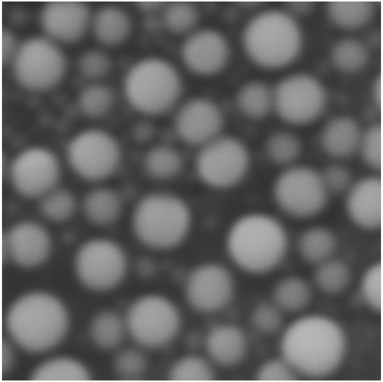
Experiment 1: Gold on Carbon Pela Standard 617-4



Contrast Transfer Function

- The Contrast Transfer Function (CTF) plots of three SEM images.
- Our restored image yields a better CTF value to that of the observed image.

Experiment 2: Tin Ball Standard Pela 620-a



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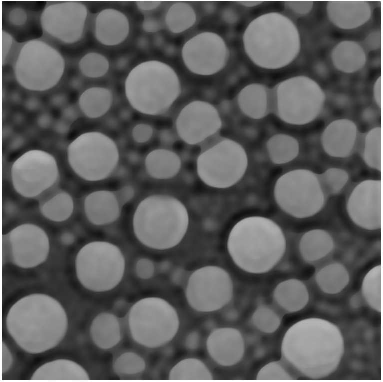
- The observed image is blurry.

Experiment 2: Tin Ball Standard Pela 620-a



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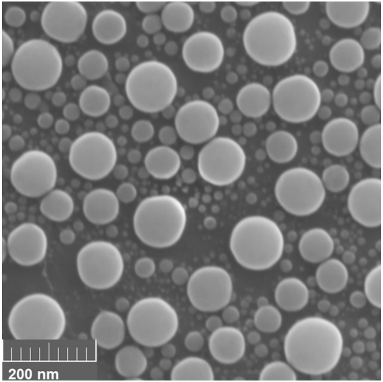
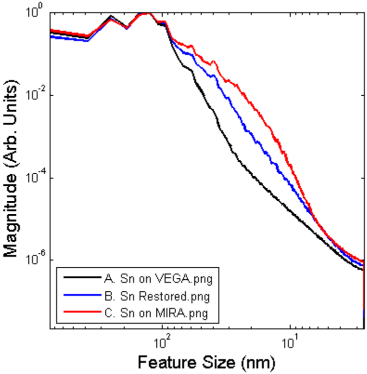


Reference Image

- Gold on Tin Ball Standard Pela 620-a

Experiment 2: Tin Ball Standard Pela 620-a



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- We have developed a new semi-blind restoration algorithm using hybrid L_1 and L_2 regularization to improve the SEM image resolution
- The new method employs an alternating-direction optimization method to solve the minimization problem.
- We demonstrated the effectiveness of our new restoration algorithm by producing higher resolution images from beam blurred images taken at high magnification in a thermionic source microscope.

Acknowledgements

- This work was supported by ......